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(71) Applicant (*for all designated States except US*): IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY & MEDICINE [GB/GB]; Exhibition Road, London WW7 2AZ (GB).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): TAYLOR, James, Roy [GB/GB]; 13 Lynton Road, Queen's Park, London NW6 6BD (GB). CHERNIKOV, Stanislav Viktorovich [RU/GB]; 28 Merton Hall Gardens, Wimbledon, London SW20 8SN (GB). GAPONTSEV, Valentin Povlovich [RU/RU]; IRE Polus, 1 Vvedenskogo Square, Fryazino, Moscow, 141120 (RU).

(74) Agents: MAGGS, Michael, Norman et al.; Kilburn & Strode, 30 John Street, London WC1N 2DD (GB).

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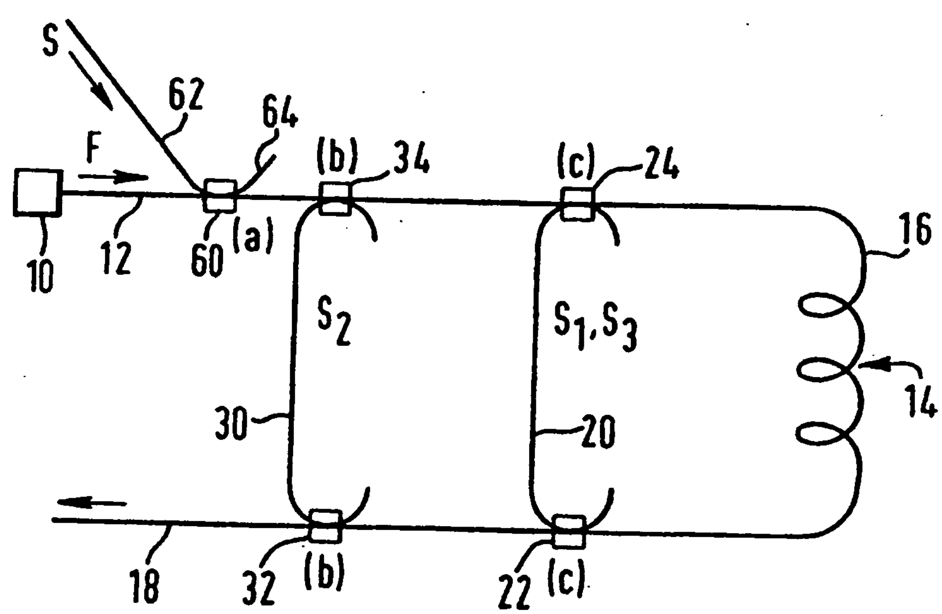
(54) Title: A RESONANT CASCADE-RAMAN RADIATION SOURCE



(57) Abstract

A resonant cascade-Raman radiation source comprises a long optical fibre which is adapted for producing Raman radiation when pump radiation is passed along it. One or more additional optical fibres are coupled across the main optical fibre to produce individual optical resonator circuits each of which resonates at a particular Stokes frequency. Cascaded Raman scattering occurs within the device, allowing access to higher Stokes components via suitably-positioned optical coupler within one of the loops. In one embodiment, the device acts as an optical amplifier, and in another it acts as an efficient radiation source (laser). Applications include optical telecommunications and remote sensing, including pollution monitoring.

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A Resonant Cascade-Raman Radiation Source

The invention relates to a resonant cascade-Raman radiation source.

Much work has been done on Raman radiation over the years. When a laser is used to produce an optical signal through an optical fibre a cascade at varying frequencies is created. Under normal circumstances, this radiation naturally dies off. However, it has been noted that in an appropriate resonator the first frequency (known as the first Stokes component) may build up enough to stimulate further Raman scattering in its own right, thereby creating a second Stokes component. That component may itself undergo Raman scattering to produce a third Stokes component, and so on. Although it has long been realised that access to second and higher order Stokes components would be a desirable aim, there is no current device which provides such access at anything like commercially-useful efficiency.

Although not for the same purpose as the present invention, a device making use of Raman scattering processes is shown in EP-A-0286338.

It is an object of the present invention to provide a high efficiency source of optical radiation. It is a further object to provide a source of radiation at wavelengths which otherwise may be difficult to achieve using other means.

According to a first aspect of the present invention there is provided a resonant stimulated cascade-Raman radiation source comprising an optical pump an output of which is coupled into a main waveguide having a Raman scattering portion within which the pump output is scattered to generate a first Stokes component, a first re-entrant waveguide portion which forms, with the Raman scattering portion, a first re-entrant loop within which

the first Stokes component resonates, the first Stokes component itself being Raman scattered within the Raman scattering portion to generate a second Stokes component, and a first coupler within the loop for coupling out the second Stokes component.

According to a second aspect of the present invention there is provided a resonant cascade-Raman radiation source comprising an optical pump which is coupled into a main waveguide having a Raman scattering portion; a plurality of re-entrant waveguide portions each of which, together with the Raman scattering portion, defines a separate re-entrant resonant loop, the loops together forming a cascade-Raman resonant array; and coupling means for coupling out of the array an optical output of a required frequency.

A device constructed in accordance with the present invention provides a high-gain high-efficiency radiation source (laser) based upon the stimulated Raman scattering process. One advantage of this source is that it may be based upon standard fibre optical components which may be readily configured to allow efficient operation. The device may also be widely wavelength tunable. In the preferred configuration, cascaded intracavity Raman generation is employed in an resonant configuration which significantly decreases the threshold for stimulated scattering and increases the efficiency of energy transfer from the pump into the higher Raman Stokes (longer wavelength) components, leading to highly efficient operation.

A device of the present invention may be used as a radiation source, at a desired frequency, or alternatively as a radiation/optical amplifier. In either case, the device may be operated either in a pulsed mode or in a continuous wave mode.

The device has applications in optical telecommunications technology, and in remote sensing applications, for example pollution monitoring. In the former case, the device may be operated broadly around 1.48μm for remote pumping of Er-based optical amplifiers in the third telecommunications window, tunable around 1.55μm; or at around 1.3μm for optical amplificatic. In the second case, the device may be operated in the 2 - 3μm region.

The present invention may be carried into practice in a number of ways and two specific embodiments will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows in schematic form a resonant cascade-Raman radiation source according to a first embodiment of the present invention;

Figure 2 shows a variation of the source shown in Figure 1 which is adapted to act as an optical amplifier; and

Figure 3 illustrates the transmission functions of the couplers shown in Figures 1 and 2.

Figure 1 shows, in schematic form, a resonant cascade-Raman radiation source according to a first embodiment of the present invention.

The device includes an optical pump 10 producing a pump output at a frequency F, the output being coupled into the input end 12 of a main optical fibre 14. The fibre has a central Raman scattering portion 16, of a length optimised for operational pump power and wavelength requirement (typically 1 - 3km), and an output portion 18.

Linked between opposite ends of the Raman scattering portion 16 is a first additional optical fibre 20. This is optically coupled to the main fibre 14 by first and

second wavelength division multiplexed (WDM) fused fibre couplers 22,24. Within each coupler, the respective fibres are brought closely together, and are fused in a position adjacent to one another, so that optical coupling may occur between the cores of the fibres. This is established and well-known technology. The ends 26,28 of the additional fibre 20 are simply cut shor. no special termination is required.

In a similar way, there is also a second additional fibre 30 which is coupled to the main fibre 14 by third and fourth WDM fused fibre couplers 32,34. Again, the ends 36,38 of the fibre 30 are simply cut off.

Operation of the device relies upon Raman scattering occurring in the Raman scattering portion 16 of the main fibre 14. To that end, the fibre 14 needs to be chosen according to the power and/or wavelength of the optical output of the source 10. Depending on the power and on the wavelength, the fibre 14 may be a silica glass fibre, or alternatively a fluoride glass fibre. Other types of doping, such as phosphorous, germanium or boron may be used in appropriate circumstances.

The couplers 22,24,32,34 are of two different types, labelled (b) and (c) in the drawing. The transmission properties of the couplers are shown in Figure 3, in which transmissivity is plotted as a function of wavelength. In Figure 3, and in the description that follows, F represents the pump frequency, and S_1, S_2, S_3 and S_4 represent respectively the first to fourth Stokes lines which are generated within the Raman scattering portion 16.

The operation of the device of Figure 1 will now be described. Since both the couplers 24 and 33 are transmissive to radiation of frequency F, the pump radiation passes through to the Raman scattering portion

16. Within that portion, stimulated Raman scattering occurs and a first Stokes component is generated, of frequency S_1. As will be seen in Figure 3, the coupler 22 has zero transmissivity at frequency S_1, and the first Stokes component is accordingly diverted or "reflected" into the first additional optical fibre 20. This can in effect be the arms of the couplers 22,24. Since the coupler 24 also has zero transmissivity to the S_1 component, that component is again reflected at the coupler 24 away from the cut end 26 and back into the loop. Losses within the loop at the frequency S_1 are small, and resonance occurs. The intensity of S_1 accordingly builds up until it is large enough to undergo Raman scattering itself within the Raman scattering portion 16. A second Raman component S_2 is accordingly generated.

When light of frequency S_2 reaches the coupler 22 it passes straight through to the optical coupler 32. This coupler is of the second type, type (b), and it has zero transmissivity at S_2 frequency. The S_2 component is therefore redirected or "reflected" into the second additional optical fibre 30. At the coupler 34 the S_2 component is again reflected away from the cut end 38 back into the main fibre 14. The path is repeated, and light at frequency S_2 accordingly resonates within the loop including the Raman scattering portion 16 of the main optical fibre, and the second additional optical fibre 30. Once the intensity of the S_2 has been built up sufficiently, further Raman scattering will occur in the Raman scattering portion 16, thereby generating a third Raman component S_3.

The S_3 component is not transmitted by the coupler 22, and accordingly is reflected into the first additional optical fibre 20. At the other end of that

fibre, the component is reflected away from the cut end 26 back into the loop. Resonance at the third Stokes frequency S_3 accordingly builds up in the loop including the Raman scattering portion 16 and the first additional optical fibre 20.

The resonating component S_3 is further scattered in the Raman scattering portion 16 to generate a fourth Raman component S_4. As may be seen in Figure 3, both the coupler 28 and the coupler 36 transmit at the S_4 frequency, allowing the fourth Stokes component to exit the device along the output portion 18 of the line.

It will be appreciated that Figure 1 merely illustrates the general principles of the device, and that additional stages could be incorporated to allow access to higher Stokes orders. It is well within the capabilities of a person skilled in the art to create WDM fused fibre couplers having appropriate transmissivity characteristics to access whichever Stokes component is required. Additional couplers (not shown) may be provided as required to couple out whichever Stokes frequencies are needed. Naturally, if a large proportion of any given Stokes component is extracted from the resonant system, further cascading will not take place. However, by designing appropriate couplers only a limited proportion of any required Stokes component need be extracted, providing the possibility of leaving enough of that component within the resonating system to stimulate further cascades. In this way, several different Stokes components could be accessed at once.

The system shown in Figure 1 provides access to Stokes components S_2, S_3 and S_4 at very low pump powers.

Although the above description has focused on light travelling around the re-entrant loops in a clockwise direction, it should be understood that because resonance

has built up in each of the loops, the loops are essentially bi-directional, and it would be equally valid to talk of the light travelling in the opposite direction (at least for the continuous wave case; not so for pulsed light).

Figure 2 shows an alternative embodiment, in which the device is arranged as an optical amplifier for amplifying an input signal S. The signal S should lie within the Raman scatter provided by the pump; this need not be very close: as an example, for silica fibre the peak of Raman gain is approximately 440 wavenumbers from the pump line. The signal S arrives along an input signal optical fibre 62, which is coupled into the main optical fibre 14 via an input WDM fused fibre coupler 60. This coupler is of type (a) and has the transmissivity function shown by the correspondingly labelled line in Figure 3. The end portion 64 of the signal input optical fibre 62 is simply cut off.

Such an arrangement allows amplification of the signal S by means of a conveniently-available pump frequency F. By appropriate selection of the properties of the main optical fibre, the Raman shifts may be adjusted so that the output frequency along the output portion 18 corresponds with the frequency S. The input signal S is chosen such that it will lie within the gain band width of one of the Stokes components. This allows one to select a pump source 10 which is cheap and readily available.

In the example of Figure 2, S_4 will transmit through the system to the output line 18. S_4 is also the frequency of the signal S which is input along the line 62. In the Raman active medium 16 the fundamental F will generate S_1, which will in turn cascade to S_2 and S_3. The S_3 will act as a pump for the S_4 which is of course the

low level signal to be amplified. Accordingly, the device effectively acts as a single path amplifier for the signal S, with the resonator simply providing sufficient pump radiation at S_3 for the amplification to occur.

In effect, therefore, the amplifier is a simple single pass amplifier, with the signal passing throu the pump once and receiving gain as it does so. The pump radiation F is used up in amplifying the signal.

It will be appreciated that both in Figure 1 and in Figure 2, the pump frequency F is transmitted by all of the couplers. It may therefore appear on the output fibre 18, and if necessary another WDM filter may be placed on the output line to remove the pump radiation from the required output signal. Clearly, however, if the Raman gain fibre is correctly chosen, the cascade process will transfer with very high efficiency pump power to the Raman orders. This should mean that all or substantially all of the pump radiation is used up in the cascade process.

The system shown in Figure 2 is tunable in that the Raman gain band width is several hundred wavenumbers wide (a wavenumber being one inverse centimetre). Any signal S lying within the gain bandwidths will be amplified. Therefore, it is possible to input a signal wavelength which is tunable, and it will receive gain. The only requirement is that the signal lies within the Raman gain line width. If the input signal wavelength is tuned, the output will follow accordingly and will be amplified. However, tunability may be limited by the actual WDM filters used, and this has to be taken into account when designing the system. Any of the Stokes bands may be accessed, and all of them provide wide tunability.

There are numerous commercial applications for devices manufactured in accordance with the present invention. A first commercial application relates to remote sensing, for example for the detection of gas or air pollution. Gases have a specific vibration and certain gases produce fingerprint vibrations wh. irradiated with infra-red radiation. Typically, radiation within the 2 - 3μm range could be used, provided by a device as previously described, using a fibre optimised for operation in this wavelength regime. Currently, there are no similar small tunable laser sources for wavelengths within this range. A device of this type could also be used to study back scatter from the atmosphere.

A further application exists in the telecommunications field, where erbium amplifiers are used to boost signals within very long runs of optical fibres, for example runs of greater than around 500 to 1000 km. A device of the type described above may be used to provide remote pumping at about 1.5 μm, thereby avoiding the necessity of putting amplifiers and associated electronics under water. The pump energy could either be supplied along the signal line, or along a separate dedicated optical fibre. In this way, a resonant system source, operating at say 1W or substantially above, could act as a continuous wave remote pump.

A third application, again in the telecommunications field, is as an optical signal amplifier operating at around 1.3μm. This would remove the necessity for optical signal regeneration at around 40km intervals, and it is applicable to the majority of currently - installed terrestrial systems. A device such as is illustrated in

Figure 2 would permit all-optical transmission without having to convert back to electrical signals at intervals.

CLAIMS:

1. A resonant stimulated cascade-Raman radiation source comprising an optical pump an output of which is coupled into a main waveguide having a Raman scattering portion within which the pump output is scattered to generate a first Stokes component, a first re-entrant waveguide portion which forms, with the Raman scattering portion, a first re-entrant loop within which the first Stokes component resonates, the first Stokes component itself being Raman scattered within the Raman scattering portion to generate a second Stokes component, and a first coupler within the loop for coupling out the second Stokes component.

2. A radiation source as claimed in Claim 1 in which the first re-entrant waveguide portion comprises a separate waveguide which is coupled to opposite ends of the Raman scattering portion of the main waveguide by the first coupler and a second coupler.

3. A radiation source as claimed in Claim 2 in which the first coupler couples the second Stokes component out of the first re-entrant loop into an output portion of the main waveguide.

4. A radiation source as claimed in Claim 1 in which the first re-entrant waveguide portion comprises a re-entrant portion of the main waveguide which is coupled back to an end of the Raman scattering portion by a second coupler.

5. A radiation source as claimed in Claim 4 in which the first coupler is positioned between the Raman

scattering portion of the main waveguide and the re-entrant portion, and couples the second Stokes component out into a separate output waveguide.

6. A radiation source as claimed in any one of Claims 1 to 5, including a second re-entrant waveguide portion which forms, with the Raman scattering portion, a second re-entrant loop.

7. A radiation source as claimed in Claim 6 in which the second Stokes component resonates within the second re-entrant loop.

8. A radiation source as claimed in Claim 7 in which the second Stokes component is scattered within the Roman scattering portion to generate a third Stokes component.

9. A radiation source as claimed in Claim 8 in which the third Stokes component resonates within the first re-entrant loop, the third Stokes component being scattered within the Raman scattering portion to generate a fourth Stokes component, the fourth Stokes component being then coupled out of the second re-entrant loop.

10. A radiation source as claimed in any one of Claims 6 to 9 including third and fourth couplers coupling the second re-entrant portion to the main waveguide at opposite ends of the Raman scattering portion.

11. A radiation source as claimed in Claim 1 including a plurality of re-entrant waveguide portions each of which forms, with the Raman scattering portion, a separate re-entrant loop, and an output coupler for coupling out of one of the loops an optical output of a

required frequency.

12. A radiation source as claimed in any one of Claims 1 to 11 in which the main waveguide is an optical fibre.

13. A radiation source as claimed in Claim 12 in which the optical fibre is a silica glass fibre.

14. A radiation source as claimed in Claim 12 in which the optical fibre is a fluoride glass fibre.

15. A radiation source as claimed in Claim 12 in which the or each coupler is a fused-fibre coupler.

16. A radiation source as claimed in Claim 12 in which the optical fibre is doped with germanium, phosphorous or boron.

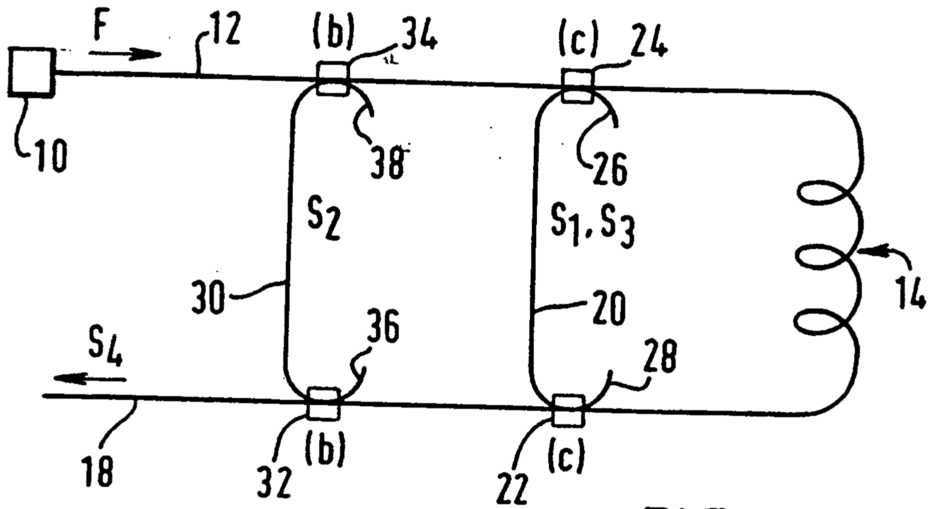
17. A radiation source as claimed in any one of Claims 1 to 16 in which the source is pulsed.

18. A radiation source as claimed in any one of Claims 1 to 16 in which the source is continuous-wave.

19. A radiation source as claimed in any one of Claims 1 to 16 including an input coupler for coupling into the Raman scattering portion the pump output and an input signal to be amplified.

20. A resonant stimulated cascade-Raman radiation source comprising an optical pump which is coupled into a main waveguide having a Raman scattering portion; a plurality of re-entrant waveguide portions each of which, together with the Raman scattering portion, defines a separate re-

entrant resonant loop, the loops together forming a cascade-Raman resonant array; and coupling means for coupling out of the array an optical output of a required frequency.


F
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(c)
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S_4
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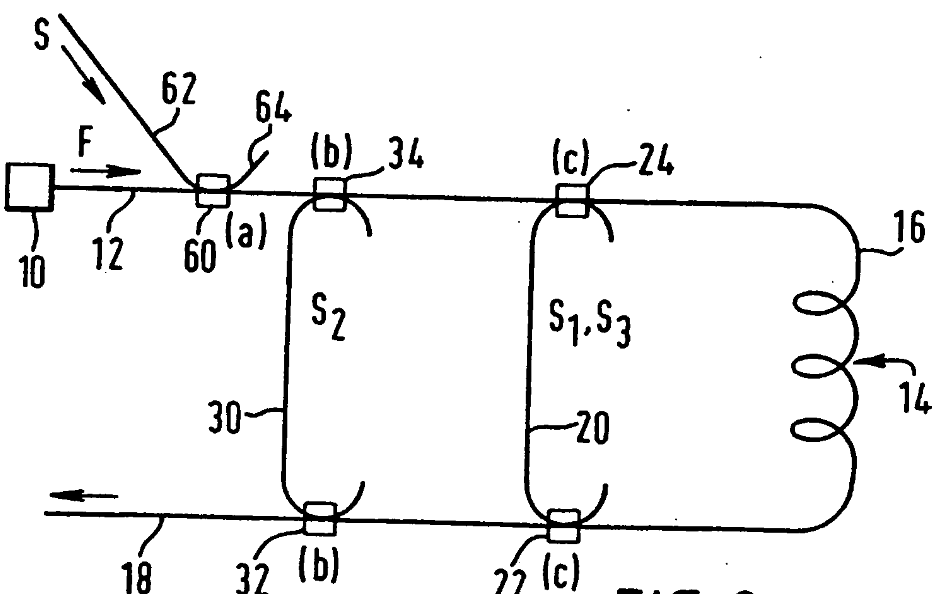
(c)

FIG. 1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(b)
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(c)

FIG. 2

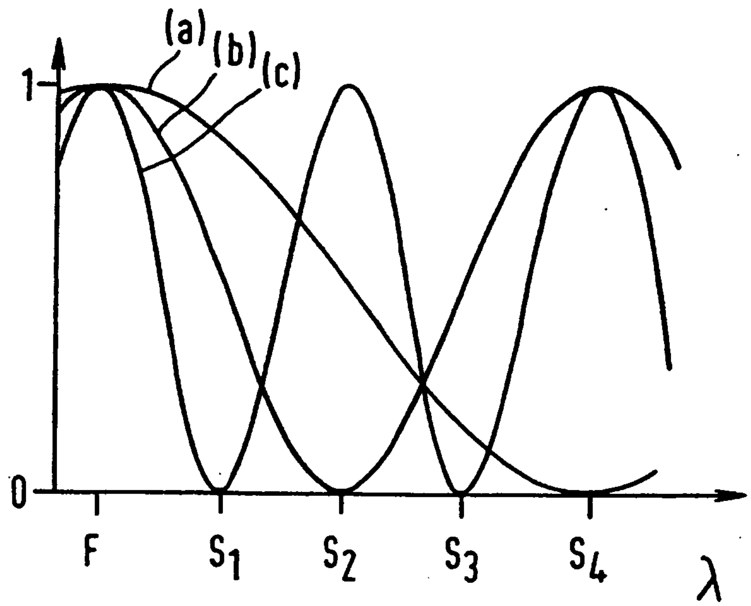

FIG. 3

INTERNATIONAL SEARCH REPORT

Int ional Application No
PCT/GB 96/01218

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/30

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ELECTRONICS LETTERS, 16 MARCH 1995, UK, vol. 31, no. 6, ISSN 0013-5194, pages 472-473, XP000530327 CHERNIKOV S V ET AL: "High-gain, monolithic, cascaded fibre Raman amplifier operating at 1.3 mu m" see the whole document ---	1-20
A	US,A,5 323 404 (GRUBB STEPHEN G) 21 June 1994 see figures 1,4 ---	1
A	EP,A,0 286 338 (BRITISH TELECOMM) 12 October 1988 cited in the application see abstract -----	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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1

Date of the actual completion of the international search	Date of mailing of the international search report
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Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

In   ional Application No
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-5323404	21-06-94	EP-A- 0651479	03-05-95
		JP-A- 7181529	21-07-95
EP-A-0286338	12-10-88	AU-B- 591591	07-12-89
		AU-B- 1492688	04-11-88
		DE-A- 3880729	09-06-93
		WO-A- 8808150	20-10-88
		JP-T- 1503570	30-11-89
		US-A- 4958910	25-09-90